Patent Application of

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for

Method and Wireless Communications Systems using Coordinated Transmission and Training for Interference Mitigation

CROSS-REFERENCE TO RELATED APPLICATIONS

This application is a continuation of copending U.S. application no. 09/432,295, filed 11/2/99.

FIELD OF THE INVENTION

The present invention relates generally to wireless communication systems and methods of operating such systems to mitigate interference with the aid of coordinated transmission and training.

BACKGROUND OF THE INVENTION

Wireless communication systems serving stationary and mobile wireless subscribers are rapidly gaining popularity. Numerous system layouts and communications protocols have been developed to provide coverage in such wireless communication systems.

Currently, most wireless systems are broken up into separate coverage areas or cells. Typically, each cell has a base station equipped with an antenna for communicating with mobile or stationary wireless devices located in that cell. A cellular network consists of a number of such cells spanning the entire coverage area. The network has an assigned frequency spectrum for supporting communications between the wireless devices of subscribers and base stations in its cells. One of the constraints on a wireless communication systems is the availability of frequency spectrum. Hence, any wireless system has to be efficient in using its available frequency spectrum.

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It is well-known that attenuation suffered by electromagnetic wave propagation allows wireless systems to re-use the same frequency channel in different cells. The allowable interference level between signals transmitted in the same frequency channel determines the minimum separation between cells which can be assigned the same frequency channel. In other words, frequency channel re-use patterns are dictated by the amount of Co-Channel Interference (CCI) seen by the receiving unit (either the base station or the wireless subscriber device).

As an example of frequency re-use, Fig. 1 shows a portion or a cluster **10** of a typical wireless cellular system with a 7*3 re-use schedule, i.e., spatial channel re-use factor 7 and 3 sectors using different frequency channels in each cell **12**. In the 7*3 case the available frequency spectrum is divided into 21 channels or sub-channels labeled by f_1, f_2, ..., f_{21}. Frequencies f_1, f_2, f_3 are used in cell **12A**, frequencies f_4, f_5, f_6 are used in cell **12B** and so on. There is no frequency re-use within cluster **10**.

Fig. 1B shows a system **14** built up of clusters **10**. As can be seen, the closest cell which re-uses the same frequency channel is at least three cells away. This separation ensures that sufficient attenuation is experienced by the signals emitted in the cells of one cluster before reaching cells of the next cluster re-using the same frequencies in its cells to not impair communications. The capacity of system **14** is dictated by the bandwidth of the channels and the carrier-to-interference (C/I) ratio. The sustainable re-use structure, therefore, decides the spectral efficiency of the system which is measured in the amount of information transmitted per unit frequency per cell, commonly measured in bps/Hz/cell.

Clearly, high spectral efficiency is a desirable system characteristic. By reducing CCI the C/I ratio can be improved and the spectral efficiency increased. Specifically, improved C/I ratio yields higher per link bit rates, enables more aggressive frequency re-use structures (closer spacing between cells re-using the same frequency channels) and increases the coverage of the system.

It is known in the communication art that receiving stations equipped with antenna arrays, rather than single antennas, can improve receiver performance. Antenna arrays can both reduce multipath fading of the desired signal and suppress interfering signals or CCI. Such arrays can

consequently increase both the range and capacity of wireless systems. This is true for instance of wireless cellular telephone and other mobile systems.

In mobile systems, a variety of factors cause signal corruption. These include interference from other cellular users within or near a given cell. Another source of signal degradation is multipath fading, in which the received amplitude and phase of a source varies over time. The fading rate can reach as much as 200 Hz for a mobile user traveling at 60 mph at PCS frequencies of about 1.9 GHz. In such environments, the problem is to cleanly extract the signal of the user being tracked from the collection of received noise, CCI, and desired signal portions summed at the antennas of the array.

In Fixed Wireless Access (FWA) systems, e.g., where the receiver remains stationary, the signal fading rate is less than in mobile systems. In this case, the channel coherence time (i.e., the time during which the channel estimate remains stable) is longer since the receiver does not move. Still, over time, channel coherence will be lost in FWA systems as well.

Antenna arrays enable the system designer to increase the total received signal power, which makes the extraction of the desired signal easier. Signal recovery techniques using adaptive antenna arrays are described in detail, e.g., in the handbook of Theodore S. Rappaport, *Smart Antennas, Adaptive Arrays, Algorithms, & Wireless Position Location*; and Paulraj, A.J et al., "Space-Time Processing for Wireless Communications", IEEE Signal Processing Magazine, Nov. 1997, pp. 49-83.

Some of the techniques for increasing total received signal power use weighting factors to multiply the signal recovered at each antenna of the array prior to summing the weighted signals. Given that antenna arrays offer recognized advantages including greater total received signal power, a key issue is the optimal calculation of the weighting factors used in the array. Different approaches to weight generation have been presented in the art.

If the channels of the desired and interfering signals are known, the weight generation technique that maximizes the signal-to-interference-plus-noise ratio (SINR), as well as minimizes the mean squared error (MMSE) between the output signal and the desired output signal, is the well-known Weiner-Hopf equation:

$$w = \left[R_{xx}\right]^{-1} r_{xd},$$

where r_{xd} denotes the crosscorrelation of the received signal vector x with the desired signal, given by:

$$r_{xd} = E[x^* d],$$

where d is the desired signal, and R_{xx} is the received signal correlation matrix, which in turn is defined as:

$$R_{xx} = E[x^* x^T],$$

where the superscript * denotes complex conjugate and T denotes transpose.

Of course, this technique, also known as the beamforming approach, is only one of many. Other prior art techniques include joint detection of signal and interferers, successive interference canceling as well as space-time or space-frequency filtering and other techniques. More information about these techniques can be found in the above-cited references by Theodore Rappaport and Paulraj, A.J., as well as other publications.

Interference mitigation including CCI reduction for the purpose of increasing spectral efficiency of cellular wireless systems particularly adapted to a system using adaptive antenna arrays has been addressed in the prior art. For example, U.S. Pat. No. 5,819,168 to Golden et al. examines the problem of insufficient estimation of CCI and noise in communication channels which leads to an inability to suppress interference. In particular, Golden teaches to solve the problems associated with correct estimation of the R_{xx} correlation matrix by an improved strategy for determining the weighting coefficients to modify R_{xx} based on the ratio of interference to noise.

U.S. Pat. No. 5,933,768 to Sköld et al. addresses the problem of interference suppression with little knowledge of the interfering signal. This is done by detecting a training sequence or other portion of the interfering signal, estimating the interferer channel and using this information in a joint demodulation receiver. The training sequences come from a finite set of known training sequences. Furthermore, the training sequences of the interferers arrive at the receiver at undetermined times. The channel estimation is performed user by user and results in poor channel estimates of the interferers since their training sequences can overlap the higher powered random data sequence of the desired user signal.

In yet another communication system as taught in U.S. Pat. No. 5,448,753 to Ahl et al. interference is avoided. This is done by coordinating the direction and transmission times of the beams such that they do not cross. In this manner interference between switched beams in a

network and especially between beams from adjacent base stations can be avoided. A significant effort has to be devoted to coordination between the users and the base stations in this scheme.

Unfortunately, the above-discussed and other methods to improve spectral efficiency by CCI suppression in wireless systems including adaptive antenna array systems do not exhibit sufficiently high performance. Thus, it would be desirable to improve interference suppression in wireless systems including systems using adaptive antenna arrays. In particular, it would be desirable to improve CCI suppression such that a higher rate of frequency re-use could be employed in wireless systems.

OBJECTS AND ADVANTAGES OF THE INVENTION

Accordingly, it is a primary object of the present invention to provide a method to mitigate the effects of Co-Channel Interference (CCI) and a wireless system adapted to practice this method.

It is a further object of the invention to provide for a sufficient level of CCI suppression to enable a higher frequency re-use in cellular wireless systems.

Yet another object of the invention is to adapt the method for use in wireless systems employing adaptive antenna arrays to further increase CCI suppression performance.

The above objects and advantages, as well as numerous other improvements attained by the method and apparatus of the invention are pointed out below.

SUMMARY

The objects and advantages of the invention are achieved by a method for interference mitigation in a wireless communication system having multiple transmitters and receivers. In a first embodiment of the method, at least a first transmitter and a second transmitter of the system transmit a first signal S_1 and a second signal S_2 respectively both at a frequency f_1. One of the receivers located within a coverage area receives first and second signals S_1, S_2. In accordance with the method a time delay is determined between reception at a specific point in the coverage area of the first and second signals S_1, S_2. Then, a transmission delay τ between the transmission of the first signal S_1 and the transmission of the second signal S_2 is introduced such that signals S_1, S_2 are received coherently at that specific point in the coverage area. Because of that, signals S_1, S_2 are received substantially coherently or even coherently (when the

point is at the location of the receiver) by the receiver. This coherent reception aids in interference mitigation.

The specific point in the coverage area can be located at the position of the receiver and can be determined by ranging. Alternatively, the distribution of the receivers in the coverage area is examined and the center of their distribution is determined. The specific point in the coverage area is substantially coincident with the center of the distribution. Frequently, this point will be located on an axis of symmetry of the coverage area. For example, when the coverage area is a sector of a cell, the point can be located on the axis of symmetry of that sector.

Now, when first signal S_1 is the useful signal and signal S_2 is an interfering signal the method calls for estimating the channels of signals S_1, S_2 and applying a method of interference mitigation in recovering signal S_1. Depending on the system, the method of interference mitigation can include beamforming, joint detection, successive interference canceling, space-time filtering, space-frequency filtering or any other suitable technique or combination.

To further aid in interference mitigation, it is preferable that signals S_1, S_2 be assigned a first and a second training pattern respectively. The training patterns are chosen to be distinguishable by the receiver. Furthermore, the patterns are selected to optimize interference mitigation. In some embodiments the patterns can also be adapted to system operating parameters such as communication traffic volume. Additionally, the training patterns can be selected based on a feedback parameter, e.g., a measure of the quality of interference mitigation, obtained from the receiver.

The present method is preferably used in wireless communication systems which re-use frequencies such that the first and second transmitters transmit signals at the same set of predetermined frequencies f_1, ..,f_n. The method can be used in bidirectional communications, e.g., in the downlink and uplink.

A wireless system of the invention can re-use frequencies more aggressively. For example, in the downlink the transmitters can be base stations in two cells located in close proximity or even adjacent each other. The receiver can be a mobile or fixed wireless subscriber device. In the uplink the transmitters are typically wireless subscriber devices and the receiver can be a base

station. In either case the wireless subscriber devices and the base stations can use antenna arrays to further aid in interference mitigation in accordance with known techniques.

The base stations can be controlled by a base station control, as is known in the art. In one embodiment, the base station control is responsible for introducing the transmission delay, τ.

The method of the invention can be used in any cellular wireless system which takes advantage of frequency re-use and seeks to reduce CCI. The method is particularly well-suited for use in systems which employ antenna arrays in its transmitters and receivers for interference mitigation. A wireless communication system employing the method of the invention has a mechanism for determining a time delay between reception of signals at the specific point in the coverage area. It also has a coordinating mechanism for introducing the transmission delay τ. The wireless system can be a Time Division Multiple Access system (TDMA), Code Division Multiple Access (CDMA), Frequency Division Multiple Access (FDMA) or other multiplex communication systems using a multiple access method or a combination of such methods.

The base station control or even the master station control of the wireless system have the necessary mechanisms or circuitry for performing the functions called for by the method, such as the coordinating mechanism for introducing transmission delay τ. In addition the base station control can have a training unit for assigning the training patterns.

Preferably, an analyzer is provided for analyzing the interference between the signals at the receiver. In fact, the analyzer is preferably a part of the receiver. In any event, it is preferable that the analyzer and the training unit are in communication and that the analyzer generate a feedback parameter indicating a quality of interference mitigation. This feedback is sent to the training unit which uses it in assigning training patterns.

In another method of the invention the training patterns are assigned to the signals and the coordinated reception at the receiver is such that the training patterns are received coherently at the specific point in the coverage area and substantially coherently by the receiver. This method can be implemented in a wireless system equipped with a training unit for assigning the training patterns, as described above. A detailed description of the invention and the preferred and alternative embodiments is presented below in reference to the attached drawing figures.

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BRIEF DESCRIPTION OF THE FIGURES

DETAILED DESCRIPTION

The method of coordinated transmission to ensure substantially coherent reception of signals in accordance with the invention will be best understood by first reviewing a portion of a wireless system **11** having three cells **13A, 13B, 13C** with corresponding base stations **15A, 15B, 15C** as shown in Fig. 2. Base stations **15A, 15B, 15C** transmit signals S_1, S_2, S_3 at the same frequency f_1 within sectors **17A, 17B, 17C**. A receiver **32**, which can be a fixed or mobile wireless device is shown in sector **17A**.

For coherent reception of signals S_1, S_2, S_3 at receiver **32**, proper transmission delays τ_o, τ_1, τ_2 have to be introduced at base stations **15A, 15B, 15C**. Specifically, in the position shown

receiver **32** is at distances d'_o, d'_1 and d'_2 from base stations **15A**, **15B**, **15C** respectively. Thus, for coherent reception, transmission delays τ_o, τ_1, τ_2 are calculated based on those distances and introduced as shown in the diagram of Fig. 3A.

In practice, receiver **32** is only one of a number of receivers (fixed or mobile) distributed throughout sector **17A**. In fact, in a typical situation the distribution of receivers throughout sector **17A** is uniform or nearly uniform. Sector **17A** has an axis of symmetry **36** and for a uniformly distributed set of receivers a center of the distribution, C.D., lies on axis **36** at the geometrical center of sector **17A** as shown. The distances from base stations **15A**, **15B**, **15C** to C.D. are d_o, d_1 and d_2 respectively. For coherent reception of signals S_1, S_2, S_3 at C.D. the transmission delays which have to be introduced are shown in the diagram of Fig. 3B.

Arranging for the transmission delays to be such that coherent reception is ensured at C.D. improves reception for all receivers in sector **17A**. Of course, receivers closest to C.D. enjoy the highest reception coherence. All receivers receive signals S_1, S_2, S_3 substantially coherently or within a short time δ, as shown in Fig. 3B for receiver **32**. Of course, as the distribution of receivers changes, especially when receivers are all mobile receivers, C.D. will tend to move somewhat. If sufficient computational capacities are provided, then the movement of C.D. can be tracked and taken into account to continuously maintain the best reception coherence for the largest number of receivers. Additionally, the cells may not be symmetrical, as shown, and more than just three cells or rather signals from more than three base stations have to be taken into account to achieve sufficient interference mitigation.

In fact, a generalized wireless system **20** employing the method of the invention in the downlink is shown in Fig. 4 to further clarify the method of the invention. System **20** has a number of cells, **22A**, **22B**, ..., **22X**, **22Y** within which radio coverage is provided by corresponding transmitting units or base stations **24A**, **24B**, ..., **24X**, **24Y** with requisite transmission devices, e.g., antennas. Cell **22X** in this example is a supercell, with its base station **24X** antenna positioned at a location providing line-of-sight communication for most signals. For example, base station **24X** antenna can be placed on a mountain top or on a high building structure. Remaining cells are standard cells which are subject to multi-path propagation of signals. Of course, any given cell can have more than one base station, or it can consist of several micro-cells with independent re-transmission units in communication with the base station. Also, the cells can be of different spatial extent. The base stations can in principle include any types of fixed or

mobile base stations, or ad hoc base stations. Alternatively, any of the base stations can be mounted on any suitable platform such as a satellite, terrestrial balloon, spaceship, etc. For simplicity these possibilities and corresponding adaptations are not shown in Fig. 4 but they will be apparent to a person skilled in the art.

Base stations **24A**, **24B**, ..., **24X**, **24Y** can send out communication signals in various frequency channels centered at corresponding center frequencies (sometimes also referred to as sub-channels) within the bandwidth or spectrum assigned to system **20**. For simplicity, the frequency channels will be referred to herein by their center frequencies or just frequencies.

In system **20** base stations **24A**, **24B**, ..., **24Y** preferably use antenna arrays or directional antennas which transmit at frequency f_1 within sectors **26A**, **26B**, ..., **26Y**. The remaining areas of cells **24A**, **24B**, ..., **24Y** may or may not be subdivided into sectors and can communicate at other frequencies which may or may not be re-used. Of course, not all antennas have to be directional, e.g., the antenna of base station **24X** is omnidirectional and communicates at f_1 within its entire coverage area.

System **20** employs a frequency re-use scheme such that signals S_1, S_2, ..., S_x, S_y are transmitted at the same frequency f_1. In fact, each of these signals S_1, S_2, ..., S_x, S_y may itself represent a group of useful signals, e.g., S_{1a}, S_{1b}, ... etc. when single base multiplexing is enabled. A person of average skill in the art will realize how to adopt the method and system of the instant invention in such situations. For purposes of clarity, however, these multiplexing options are not explicitly discussed herein.

Depending on the cell and sector in which a signal is received, it is either a useful signal or an interfering signal (interferer) contributing to CCI. In the simplest case, signal S_1 is a useful signal in sector **26A** of cell **22A**, but signals S_2, S_3, ..., S_x, S_y are all interfering signals in sector **26A** of cell **22A**. In general, however, any subset of signals S_1, S_2, ..., S_x, S_y can represent the useful signal and the remaining subset of received signals can represent the interferers, as will be apparent to a person skilled in the art familiar with spatial multiplexing techniques. For example, spatial multiplexing can be employed to provide communication of numerous signals in the same allocated bandwidth as described in U.S. Pat. No. 5,345,599. In the embodiment shown in Fig. 4 only one useful signal in each sector is shown for the sake of clarity.

In the simple scenario discussed here, although attenuation of electromagnetic radiation provides for attenuation of signals S_2, S_3, ..., S_x, S_y according to the distance they propagate to reach cell **22A**, any or all of these signals can arrive in sector **26A** of cell **22A** by a direct or multi-path route at a sufficient signal strength to represent CCI. The route or channel **28** of signal S_2 from sector **26B** of cell **22B** to sector **26A** of cell **22A** is indicated in Fig. 4. Signals S_3, S_4, ..., S_y also propagate to sector **26A** in their respective channels (not shown).

A cellular user or subscriber **30** with wireless subscriber device **32** such as a mobile, portable or stationary unit, in this case a mobile cellular telephone operating in sector **26A** receives all signals S_1, S_2, ..., S_y. To device **32** signal S_1 is the useful signal and signals S_2, S_3, ..., S_y are interferers. Interference can be mitigated by employing any suitable scheme such as, beamforming, joint detection, successive interference canceling, space-time filtering, space-frequency filtering or any other suitable technique or combination. For example, in the beamforming method a received signal correlation matrix R_{xx} contains information of the routes or channels for each of the interferers S_2, S_3, ..., S_y as well as the useful signal S_1. It is known that if the elements of the correlation matrix R_{xx} are known, i.e., if all channels are known, then the channels carrying the undesired signals can be canceled out. In the joint detection case the useful signal and interferers are detected jointly in a similar fashion using knowledge of the channels. After detection the interfering signals are removed and the useful signal(s) is kept.

Signals from cells closest to cell **22A**, i.e., adjacent cells **22B**, **22C**, as well as cells directly aligned with cell **22A**, e.g., cell **22D** along axis **36** will be least attenuated. Hence, signals S_2, S_3, and S_4 will contribute the most to CCI in sector **26A** of cell **22A**. Signals from further away along axis **36**, e.g., cell **22X** and further laterally offset from axis **36**, e.g., cell **22Y** will contribute less to CCI. In other words, signals S_x, S_y will contribute less to CCI in sector **26A** of cell **22A**. For best communication performance between base station **24A** and subscriber unit **32**, however, any interferer received by unit **32** should preferably be mitigated.

System **20** can use any suitable communication protocols for formatting the data contained in signals S_1, S_2, ..., S_y it transmits from base stations **24A**, **24B**, ..., **24Y**. A base station control (BSC) **34** and a Master Station Control (MSC) **35** which controls BSC **34** and any other BSCs (not shown) of system **20** control the transmission of signals S_1, S_2, ..., S_y. In accordance with the method, transmission delays are introduced by base stations **24A**, **24B**, ..., **24Y** under supervision of BSC **34** and/or MSC **35** such that all signals are received coherently at C.D. in

sector **26A**. This is shown in the diagram of Fig. 5A. As a result, receiver **32** receives signals substantially coherently or within a time δ as shown in the diagram of Fig. 5B.

Substantially coherent reception of signals within time δ in and of itself results in improved interference mitigation and reduced inter-symbol interference. It should be noted that guard intervals G of signals S_1, S_2, ..., S_y should preferably be kept longer than δ, because of multi-path and other effects which can broaden time δ.

In a particularly advantageous embodiment of the method each signal S_1, S_2, ..., S_y is additionally provided with a training pattern, or in this case a training sequence, tr. The actual form of the training pattern or sequence will depend on the type of system **20** and signal coding. In the case where each of the signals S_1, S_2, ..., S_y represents a group of signals, each group will need multiple training patterns. The type of training pattern for each constituent signal in each of these groups will vary depending on the type of operation. The multiple signals in each group could, for example, represent diversity streams, multiplexing streams, etc. Multiplexing streams in particular may need longer duration of training sequences (or patterns) than those required for diversity streams to ensure similar accuracy of channel estimates. In case of single carrier modulation schemes, the training pattern can be, for example, a sequence of symbols or bits. But in case of multi-carrier modulation schemes such as OFDM, the training pattern may comprise a set of frequency tones which are chosen out of the available tones in such a way that the individual tones in the set are orthogonal to each other. In this case the orthogonality between such two different training patterns or frequency tone sets can be ensured by choosing the correct constituent tones in those two sets. In the single carrier case, orthogonality between two training sequences depends on the cross-correlation between them at the receiver. A person of average skill in the art will realize what particular training patterns should be used in any particular wireless system.

In the case shown in Figs. 5A and 5B single carrier transmission is assumed and the training patterns are simple training sequences tr_1, tr_2, ... tr_y. Because of the coordinated transmission of signals, the training sequences are received substantially coherently by device **32**. In fact, thanks to the presence of guard intervals G, discussed below, the receipt of training sequences can be compensated for time δ. Such coherent reception of training patterns tr_1, tr_2, ... tr_y further aids in interference mitigation. In this case, BSC **34** is in communication with base stations **24A**, **24B**, ..., **24Y** of system **20** and with subscriber units, such as subscriber unit **32** assign training

sequences tr_1, tr_2, ..., tr_y to signals S_1, S_2, ..., S_y. The components performing this assignment will be discussed below.

The time delays with which signals S_1, S_2, ..., S_y arrive at C.D. are calculated using the known propagation speed (c=speed of light) of the electromagnetic signals and the known distances d_1, d_2, ..., d_n. Of course, even if the base stations were mobile, these distances can be periodically re-computed to determine the time delays e.g., by ranging or other distance determination techniques known in the art. In fact, ranging from any base station or even subscriber unit **32** can be used at any point in time to re-confirm or determine distances d_1, d_2, ..., d_n. It should be noted that delay times between base stations can be unequal if the cells of system **20** are not of the same size and thus the distances along axis **36** between successive base stations are unequal.

In the generalized case shown in Fig. 4 signals S_2 and S_3 experience a time delay τ_1 in propagating to base station **24A** and another time delay τ_o before being received at subscriber unit **32**. For signal S_y, which is still sufficiently strong in sector **26A** to interfere with signal S_1 and requires CCI interference mitigation, the total time delay is $\tau_o+\tau_1+\tau_2+...+\tau_n$. Clearly, it is only necessary to determine time delays for signals which contribute to CCI.

For coherent reception of signals S_1, S_2, ..., S_y and in particular of their training sequences at subscriber unit **32**, the time δ has to be taken into consideration. The guard intervals G_1, G_2, ..., G_y of duration at least equal to δ are added to signals to compensate for time δ. The use of guard intervals or bits is well-known in the art. Figs. 5A and 5B illustrate the formatting of signals in generalized system **20** of Fig. 4. Specifically, signals S_1, S_2, ..., S_y are broken up into three main constituent portions, namely their guard intervals G_1, G_2, ..., G_y, their training sequences tr_1, tr_2, ..., tr_y and their payload or data portions D_1, D_2, ..., D_y.

Because the total time of flight (TF) of signal S_y to unit **32** is the longest, S_y is transmitted first at time t_o. Signal S_x is transmitted after a transmission delay τ_n at which time signal S_y has already propagated distance d_n (see Fig. 4). In other words, S_x is transmitted at $t_o+\tau_n$ and approximately in sync with signal S_y indicated in dashed lines at $t_o+\tau_n$. After transmitting intervening signals (not shown) in the same manner, signals S_2, S_3 are transmitted at time $t_o+\tau_n+...+\tau_2$ and signal S_1 is finally transmitted at time $t_o+\tau_n+...+\tau_1$.

The above staggered transmission scheme or walking across scheme ensures that signals S_1, S_2, ..., S_y are received coherently at time TF=$t_o + \sum_{i=0}^{n} \tau_i$ at C.D. and substantially coherently at unit **32**, as indicated in dashed lines. More importantly, this scheme with additional compensation offered by guard intervals G_1, G_2, ..., G_y ensures that training sequences tr_1, tr_2, ..., tr_y are available to unit **32** simultaneously.

In accordance with one embodiment of the invention, simultaneous reception of training sequences tr_1, tr_2, ..., tr_y enables unit **32** to determine the channels of signals S_1, S_2, ..., S_y by obtaining accurate channel estimates. In other words, unit **32** can now determine the received signal correlation matrix R_{xx} and r_{xd} and successfully use, e.g., the beamforming technique for interference mitigation. Once matrix R_{xx} and r_{xd} are known, CCI can be mitigated. Of course, unit **32** can also use any of the other interference mitigation techniques mentioned above.

It is known in the art that training patterns used will impact how well the channel of the corresponding signal can be determined. In general, longer training sequences or more dense training patterns will ensure better channel estimation. On the other hand, excessively long training sequences or dense training patterns take bandwidth away from the payload. Thus, in general, training patterns should be chosen to yield sufficiently good channel estimates for interference mitigation but not unduly limit the payload size.

The above generalized description illustrates the basic principles of the method and system of the invention. These principles can be adapted to various wireless data transmission protocols and wireless systems. For example, the method of the invention can be used in a time division multiple access (TDMA) network **50**, a portion of which is shown in Fig. 6. Because this system employs the method of invention for CCI mitigation a more aggressive frequency re-use schedule is applied in network **50**. In particular, the available spectrum is subdivided into only three sub-channels f_1, f_2, and f_3 which are re-used in three sectors of each cell **52** as shown. In the figure, cells **52** are regularly spaced and of the same size, such that the distances between their centrally positioned base stations are constant. Hence, the delay times and the necessary transmission delays τ are all equal. A person skilled in the art will recognize that in practice there will be deviations in cell sizes and thus delay times may not be equal.

In order to ensure substantially coherent reception by the receivers of signals and/or their training sequences, each of the base stations has to introduce a transmission delay τ in the

manner described above. For signals transmitted at f_1 along a direction of orientation **56** of sectors operating at f_1 signals are transmitted from the most remote base station row **54A** which will produce CCI first at time t_o. Then, signals are sent at time $t_o+\tau$ from the next row **54B** of base stations which will produce interference. Finally, at time $t_o+2\tau$ signals are sent from the last row **54C** of base stations which transmit useful signals to subscriber units in the corresponding cells. Preferably, this staggered transmission or walking across network **50** scheme is performed across the entire network **50**. The same walking across scheme is utilized in transmitting signals at frequencies f_2 and f_3.

Fig. 7 illustrates a Base Station Control (BSC) **60** and/or Master Switching Center (MSC) which can be used to control part of network **50**. Only three cells **52A**, **52B**, **52C** of network **50** are shown for clarity, but it is understood that BSC **60** and/or MSC as well as any additional BSCs are appropriately connected, as is known in the art, to control all cells **52** of network **50**. In particular, BSC **60** is connected to base stations **53A**, **53B**, **53C** of cells **52A**, **52B**, **52C**.

BSC **60** has a training coordinator or controller **62** and a database of training patterns **64**. Controller **62** is connected to database **64**. The set of training patterns in database **64** can be different for different re-use structures and cellular layouts while taking into account the changing interference scenario. For example, training patterns can be different time sequences such as Walsh codes in case of system **50** which is a single carrier system. A person of average skill in the art will recognize that other codes can be used depending on the type of communication network. For example, different sets of frequency tones can be used as training patterns in Orthogonal Frequency Division Multiplex (OFDM) systems. In fact, any orthogonal or other training patterns which are distinguishable at the receiver and which aid in effective channel estimation of the interferers can be employed.

BSC **60** communicates the selected training sequences to base stations **53A**, **53B**, **53C** through a signaling block **66**. Base stations **53A**, **53B**, **53C** then use these training sequences in the signals they transmit to the subscriber units operating in their respective cells **52A**, **52B**, **52C**. For example, training sequences for all frequencies f_1, f_2, f_3 used in cells **52A**, **52B**, **52C** are of the same length and are selected from the group of Walsh code sequences.

Alternatively, the lengths and types of training sequences can be adjusted based on communication traffic volume. For instance, when no traffic exists in cell **53C** in the sector

operating at f_1 then no signals are being transmitted from it and hence no signals from that sector contribute to CCI in any other cells, e.g. in the f_1 sector of cell **53A**. Therefore, if system **50** is an OFDM system, then no training patterns are required by base station **53C** for the f_1 sector, since no signals are transmitted there. In other systems any training sequences can be kept short and the training periods long. The bandwidth which would have been allocated to the corresponding training sequence can thus be allocated to training sequences used in other cells to allow more precise channel estimation or can be used to increase the signal payloads in other cells.

On the other hand, when the traffic volume in the sector at f_1 in cell **52C** is high, its signals will have a major contribution to CCI in other cells, e.g., in the sector at f_1 in cell **52A**. Hence, preferably a long training sequence is assigned by training controller **62** to the f_1 sector in cell **52A** to enable subscriber units in other cells to obtain a sufficiently good estimate of these signals for interference mitigation. It is well-known to those skilled in the art that increasing the amount of training or the training sequence and decreasing the period of training, e.g., the times between training sequences, can improve the accuracy of the channel estimate.

The performance of interference mitigation for any particular set of assigned training sequences is preferably monitored. In this case BSC **60** has a feedback analyzer **68** for receiving performance feedback information from base stations **53A**, **53B** and **53C**. Preferably, analyzer **68** receives the signal quality feedback from the subscriber units through their respective base stations, analyzes them and passes on the results to training controller **62**. The monitoring can be performed continuously or periodically. The signal quality information can simply be a channel or link quality indication, such as individual signal strength, relative signal strength amongst other signals or the mean square error of the respective channel estimate. Feedback analyzer's **68** report to training controller **62** on the link quality can be used for determining re-assignment of training sequences by training controller **62** when the link quality drops below an acceptable threshold.

Of course, subscriber units operating in network **50** have to be told what training sequences are used by the useful signal and the interferers so that after coherently receiving the signals and training sequences they can cancel out the interferers. For this purpose, the base stations communicate the training sequence assignments to the subscriber units. This can be accomplished as illustrated in Fig. 8 on the example of base station **53A**.

Base station **53A** has a training distribution block **70**, a transceiver unit **72** and a number of antennas **74A**, ..., **74X** forming an adaptive antenna array. Although such adaptive antenna arrays are preferred, the method can also be employed in base station with a different antenna configuration or a single antenna system. However, as is known in the art, adaptive antenna arrays can use spatial-signature monitoring and provide for additional interference mitigation and are hence preferred for both base stations and subscriber units. Training distribution block **70** receives the training sequence assignments from signaling block **66** of BSC **60** and passes them on to transceiver unit **72**. Transceiver unit **72** communicates the training sequences of potential interferers and of its own signal or signals to the subscriber units within cell **52A** via antennas **74**.

Although downlink communication direction is being described at this point, in uplink communication, i.e., when subscriber units are the transmitters and base stations the receivers, the situation is analogous but reversed and it is the base stations which will mitigate interference due to signals from subscriber units. Hence, base stations **53A**, **53B**, **53C** need to know the training sequences used by the subscriber units. BSC **60** communicates to base stations **53A**, **53B**, **53C** the training sequences to be assigned to the subscriber units and the base stations use these training sequences, received in a co-ordinated manner according to the method of the invention, to mitigate CCI. Because the positions of the subscriber units are more likely to change, and will change for mobile subscriber units, ranging between subscriber units and base stations for the purpose of determination of distances and transmission delays is required in the uplink. Whereas, for fixed subscribers ranging once in a while, or at the time of intial installation may suffice.

Fig. 9 is a block diagram of a subscriber unit **80** equipped to operate in a wireless system of the invention, e.g., in network **50**. Unit **80** has an adaptive antenna array **82** consisting of antennas **82A**, ... **82X** for receiving signals. An Rf/Down Conversion/Sampling circuit **84** processes the signals received by array **82** and down-converts and samples them. After down-conversion and sampling the signals are applied to an interference mitigation block **86** which regularly receives channel estimates of signals of interest and of interferers from a multi-channel estimator **88**. A training block **90** which receives the training sequence information from the base station, selects the correct training sequence for each signal, e.g., signals of interest and the interferers, and supplies it to multi-channel estimator **88**.

Preferably, unit **80** has its own database of training sequences **92** used in network **50** (e.g., mirroring those in database **64**). In this way, the training sequences are locally available to unit **80**. The training sequences can be updated or changed to reflect those in database **64** as instructed by BSC **60**. Multi-channel estimator **88** uses the training sequences from training block **90** and down-converted signals to estimate the desired signal and interferer signal channels in parallel. Multi-channel estimator **88** is also connected to a signal quality measurement block **94** which analyzes the channel estimates and in conjunction with multi-channel estimator **88** measures the signal quality of the desired signals and interferers. This information is fed back to be transmitted via the base stations to feedback analyzer **68** and training controller **62** of BSC **60**. Analyzer **68** and training controller **62** use signal quality feedback information to assess interference mitigation performance and assign/re-assign training sequences as described above.

An example of a multi-channel estimator **100** suitable for use as estimator **88** is shown in Fig. 10A. Multi-channel estimator **100** is a Multi Input Multi Output (MIMO) Space-Time channel estimator using the Least Squares approximation. The selected training sequences for the desired signals and interferers are delivered, e.g., from training block **90**, to a transfer matrix generation unit **102**. Unit **102** produces the transfer matrix $T^H(T \bullet T^H)^{-1}$, where T is the matrix of training sequences in which each row is a particular training sequence for a desired signal or interferer and T^H is the Hermetian transpose of T.

The transfer matrix is supplied from unit **102** to a matrix multiplier **104**. Matrix multiplier **104** also receives the actual signals with their training sequences from the multiple channels. These signals include useful signals and interferers. Multiplier **104** multiplies the transfer matrix by the signals to obtain a joint MIMO channel estimate which is passed on to interference mitigation such as block **86**.

Fig. 10B shows an exemplary interference mitigation block **110** which can be used as block **86**. The channel estimate obtained from block **100** is fed to a weights computation block **112**, which computes the weights for the received signals and delivers them to a space-time equalizer **114**. Equalizer **114** can be a least squares (LS), zero forcing (ZF), minimum mean square estimator (MMSE), an ML equalizer, a successive interference canceling type equalizer or any other kind of equalizer known to those skilled in the art. Equalizer **114** applies the weights from block **112**

to the received signals during the data phase or portion and thus suppresses the interfering signal or signals to obtain the desired signal or signals.

Fig. 11 shows yet another type of interference mitigation circuitry **120** which implements an estimator **122** and an interference canceler **124** in a space-frequency wireless system, e.g., an OFDM system. In this case the training patterns contained in the signals are particular frequency tone sets and their values. There can be a dedicated training phase during which the training patterns are transmitted and a data phase during which the data are transmitted. Alternatively, the training patterns can be transmitted along with the data by allocating a dedicated subset of data tones to the training patterns.

During the training phase the channels 1 through n of the OFDM signals are received and transformed to the frequency domain by fast Fourier transform block (FFT) **126**. The transformed signals are delivered to a MIMO space-frequency channel estimator **128**. Estimator **128** is also supplied with the training patterns assigned to the desired signals and the interferers. Using these inputs estimator **128** generates the joint channel estimate, which it forwards to a space-frequency equalizer **132** of interference canceler **124**.

Equalizer **132** can be a least squares (LS), zero forcing (ZF), minimum mean square estimator (MMSE), an ML equalizer, a successive interference canceling type equalizer or any other kind of equalizer known to those skilled in the art. During the data phase equalizer **132** receives OFDM signals contained in channels 1 through n transformed to the frequency domain by FFT block **130**. Equalizer **132** uses the joint channel estimates obtained from estimator **128** to suppress the interferers and generate the desired signals at its output.

It will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.